Scientific CMOS camera technology: A breeding ground for new microscopy techniques

Gerhard Holst
Science & Research, PCO AG, Kelheim, Germany

INTRODUCTION

In 2009 a new type of complimentary metal-oxide semiconductor (CMOS) image sensor was developed by a a consortium of three companies: Fairchild Imaging (now a division of BAE Systems), Andor Technology and PCO [1]. At the time the partners decided to call the device a scientific CMOS (sCMOS for short) image sensor to make clear from the very beginning that the performance data of this new type of sensor would be very different from the usual standard CMOS image sensor. The combination of high sensitivity, low readout noise, high frame rate, high resolution and high dynamic range did not exist before, not even within the commonly used cooled CCD and electron multiplying CCD cameras, which were widely available for microscopy.

Compared with standard CMOS image sensors, the new sCMOS sensors are based on a new and optimized pixel architecture in combination with an unusual readout scheme. First, the pixels are designed so that low-noise parts like photodiodes are used as detectors. Furthermore, the main noise contributing capacitors are made sufficiently small, and correlated double sampling (like in CCD image sensors) is applied. In addition, the unusual readout with two 11-bit A/D converters achieves a smaller noise contribution compared with the application of a faster 16 bit A/D-converter. With this blend of measures the sCMOS sensor achieves a combination of performance characteristics hitherto unseen.

The first released sCMOS image sensor was the CIS2521 version with the up to now largest resolution (number of pixels). Since then, Fairchild Imaging has extended the portfolio of its sCMOS image sensors in two directions: by creating new image sensors with smaller resolutions; and by creating with Hamamatsu Photonics a variation of the original sCMOS concept by removing the global shutter operation and achieving a 10% more quantum efficiency. Based on all these interesting new image sensors, a variety of cameras for microscope applications has now been developed by numerous companies.

In this review, I give an overview on the matured sCMOS technology, discuss some of the wanted and unwanted features of these sensors, and describe with some applications how sCMOS technology has helped to either fuel or improve methods such as confocal microscopy, localization microscopy, selective plane imaging microscopy and structured illumination microscopy.

THE MAIN CHARACTERISTICS OF sCMOS SENSORS

LOW READOUT NOISE

We start with the low readout noise, which allows the discrimination of very weak signals from the background. It is a kind of prerequisite for the imaging of low-light signals. In other image sensors, such as EMCCDs, this is achieved by an amplification prior to the readout process, therefore the high readout noise figures are converted to smaller numbers. In sCMOS the readout noise is extremely low (see Table).

Since the values are the result of averaging calculations and a fit of a model to the date (Gaussian with rms or median), there are decimals present, which are not so obvious, because fractions of noise electrons do not exist. If a median readout noise value of 0.9 electrons is taken into account, it means more than 50% of the pixels have over time either one noise electron or none in the recorded images. The smaller the average value is (see figure 1) the larger the amount of images, where the corresponding pixel has no noise electron.

A second very nice effect of such a low noise is its beneficial influence on the intra-scene dynamic range (often referred to as the "dynamic" of the image sensor or camera), describing the darkest and brightest information which can be detected within one image. Simply speaking, the smaller the noise, the larger the resulting dynamic.

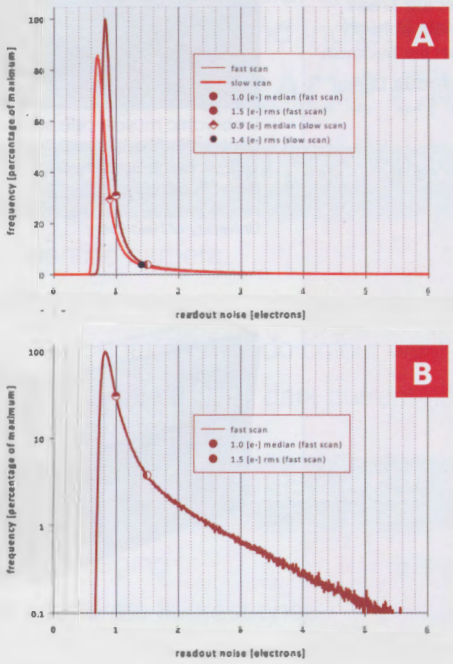

FIGURE 1 The readout noise of a CIS2020 sCMOS sensor in a pco. edge 4.2 camera was measured by recording a stack of 1000 images (full frame, 10 ms exposure time, with hot pixels and blinking pixels) for the slow and fast scan operational modes. For each pixel the standard deviation was determined and is displayed in the histogram. The values have been normalized by the maximum frequency value of the fast scan curve. (a) Both curves in a linear scaling. (b) Only the fast scan curve with y logarithmic y-axis scaling. Median and root mean square values for the different curves are also given.

HIGH SENSITIVITY

sCMOS sensors have an excellent sensitivity or quantum efficiency for photons of between 60 and 70%, which is only outperformed by back-illuminated image sensors, but it is more than sufficient for most of the relevant microscope applications.

HIGH SPEED

Perhaps one of the main advantages of CMOS image sensors is the highly parallel readout process, which enables high frame rates of up to 100 images/frames per second at full resolution (typically 2560 x 2160 pixels). If the area of interest is reduced, as in localization microscopy, the frame rate can go up to 1000 frames per second or more, and thereby accelerating the total image uptake significantly. So now a complete image is acquired in a couple of seconds compared to a couple of minutes. As a

consequence, if high frame rates are important for an application the exposure or shutter time is decreased, which in turn reduces the influence of the dark current and increases the requirement for more light. Independent of the image sensor this also increases the data load requirements for the storage system.

NOTE 1 DYNAMIC RANGE

Sometimes it takes extra effort to visualize the higher amount of information, because the user has to decide which range or how the 16-bit data are displayed in the 8-bit world of computer screens and LCD projectors.

NOTE 2 RESOLUTION

In cameras the term resolution describes the number of available pixels used to measure or detect an image. Often the high resolution in combination with the smaller pixel size can cause a problem when the sensitivity of sCMOS cameras is compared with other cameras such as EMCCD cameras. If the cameras are compared under real conditions, which is generally an excellent idea, the cameras are simply exchanged at the same port of the microscope. If the pixel size of the cameras is the same, that is perfectly OK. But if the pixel size of the sCMOS is smaller than the former image sensor, e.g. EMCCD sensors, it will go wrong. Assume a pixel size of 12 x 12 µm² of the former camera and a pixel size of 6 x 6 µm² of the sCMOS, then the former imaged light signal now has to be shared by 4 pixels, therefore only a quarter of the signal is left for each pixel, which certainly does not give any valuable information about the pixel sensitivity if both are compared. On the other hand, in most cases for a quick test it might be impossible to change the imaging optics in a way that the same image area is imaged to the same amount of pixels to achieve the same input signal per pixel. For fast test the exposure time of the cameras can be adapted in a way that the smaller pixel size camera gets accordingly longer exposures.

HIGH DYNAMIC RANGE

The intra-scene dynamic range of the sCMOS image sensors varies from 1:5000 up to 1:33,000. This dynamic is determined by the fullwell capacity of the image sensor (i.e. the maximum number of charge carriers each pixel can collect before it starts to overflow) divided by the smallest signal that can be discriminated - the readout noise.

In some weak-signal applications (e.g. single molecule) this feature is not of interest, because high contrast in a single image never occurs. However, in some larger structural applications such as slide scanning (digital pathology) it can be very interesting, since it allows for the detection of a higher amount of grey levels, offering for example more information about the structure of the sample [See Note 1].

HIGH RESOLUTION

Compared with consumer digital cameras the 5.5 or 4.2 megapixels of the larger sCMOS image sensors might not impress, but for microscopy cameras there only have been a few CCD cameras with large interline transfer CCD sensors that reached this level. Most microscope cameras have at best used resolutions of 1-1.5 megapixels, therefore the new sensors have a lot more resolution to offer [see Note 2]. This is very important for many widefield microscopy applications, where a larger area can be investigated at once instead of scanning the sample and stitching the images.

CONSIDERATIONS

Although there is no image sensor available with the same combination of attractive performance characteristics, there are some peculiarities of CMOS image sensors and image sensors in general to consider.

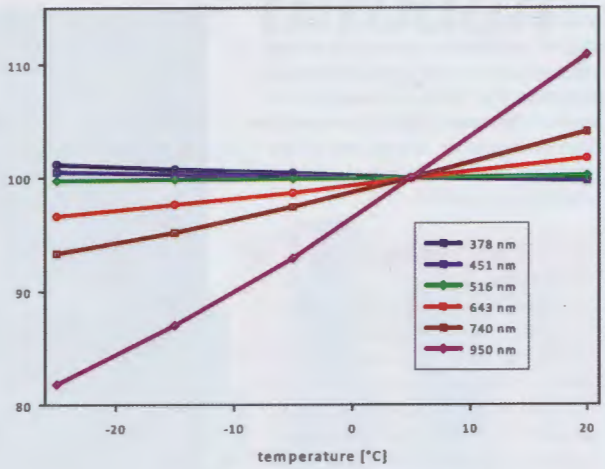

FIGURE 2, top, The relative spectral sensitivity in dependence of the temperature. For a sCMOS image sensor (CIS2521) the mean signal has been measured with different LEDs as a function of the sensor temperature. The signal has been normalized by the +5°C value. It clearly shows that for longer wavelengths the cooling of the image sensor significantly reduces the sensitivity of the sensor.

READOUT NOISE

Figure 1 shows a noise histogram of a CIS2020 image sensor (without hot pixels or a blinker filter) at two different pixel clocks. In the linear display (Figure 1a) it can be seen that the shape of the histograms does not totally look like a Gaussian distribution curve. Nevertheless the root mean square value (the result of a fit with a Gaussian shape distribution) is generally used to characterize the readout noise of a camera or an image sensor. Another option is to give the median value, which is a little bit lower, but the fit is as good or bad, like the rms value. This can be better seen in a logarithmic scaling of the same curve of the CIS2020 at the higher pixel clock, which is shown in Figure 1b. Here the long noise tail of the sCMOS image sensors can be seen. More than 50% of the pixels have noise values smaller than one electron, nevertheless a small but significant amount of pixels have larger values as well, this includes hot/warm pixels and blinking pixels which are always present in image sensors [see Note 3].

HOT/WARM AND BLINKING PIXELS

In some microscopy methods such as localization microscopy the specific noise pixels (hot/warm pixels and blinkers) were a matter of interest and discussion, because they might interfere with the determination of the position of fluorescent molecules. If and how much they interfere is a matter for research. There are publications describing how all camera filtering processes were switched off, and home-made calibration algorithms were successfully applied [2].

In general, all image sensors have this issue of defective or partially defective pixels, CCD image sensors as well. The latter do not have blinkers due to a different semiconductor structure and composition. Since it cannot be avoided in nearly all scientific cameras (in consumer cameras as well) hot/warm pixels are replaced by the average value of their neighbours. For the blinkers,

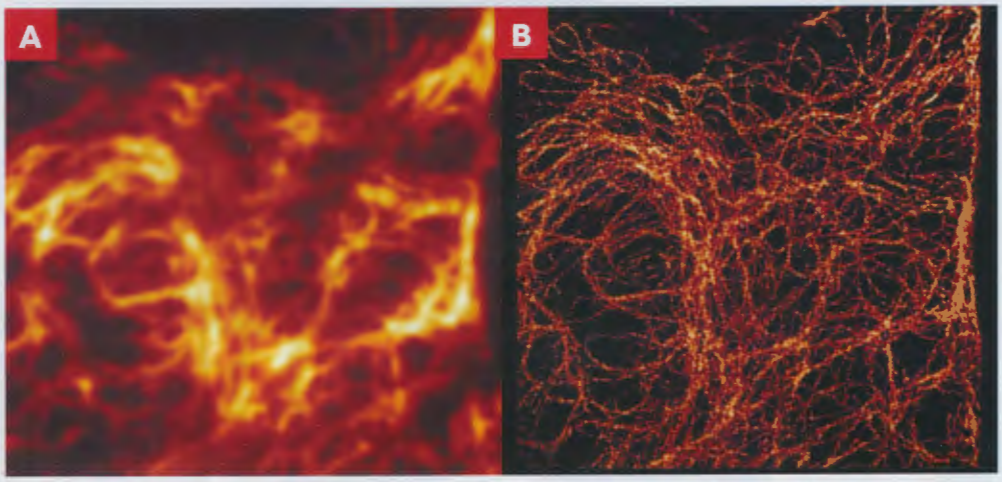

FIGURE 3, above, Ground state depletion [3] localization microscopy false colour images of vimentin, a type III intermediate filament protein, that has been stained with Alexa 647. The cells were attached to a coverslip and were illuminated in a TIRF configuration. The sCMOS camera recorded images at 1176 frames per s (0.85 ms exposure time). (a) The widefield preview image. (b) The high resolution image. The displayed area = 18 x 18 µm².

Courtesy of Leica Microsystems, Mannheim, Germany

EU

additional software filtering is usually applied, which also replaces the wrong value by some sort of a neighborhood operation. But there is no reason to be worried, because in many cameras these filter processes can be switched off, to figure out if and how much the intended results are influenced.

NOTE 3 HOT/WARM AND BLINKING PIXELS

The term hot pixel is usually used for a defective pixel, which always shows white, whereas a warm pixel has a significantly higher offset value than its neighbours, but still reacts to light. Some hot/warm pixels are related to the dark current and have therefore a relationship to temperature. Blinking pixels (blinkers) are best described as non-permanent hot pixels, caused by defects and impurities on the semiconductor, which cause very bright pixels in some images but not others, but they are localized. Hot/warm pixels are always present in CCD and CMOS sensors; blinkers are only in CMOS.

COOLING

In general cooling the sensor is a good idea if only to maintain stable temperature conditions of the image sensor. Otherwise, like all electronic devices, image sensors tend to heat up when operated and this always create changes of the behaviour of all contributing electronics, and becomes visible in a changing offset of the images. This can be cancelled out by proper temperature control. Fortunately this is independent of the absolute value of the temperature.

The second effect of cooling is the reduction of the dark current and its contribution to the total noise, but the noise contribution includes the exposure time, which puts this relation into perspective, because when using frame rates faster than 1-2 images per second the exposure time is short enough that there is no significant noise contribution by the dark current. Most of the recent applications of sCMOS cameras exploit these high available image rates. However, the numbers of hot/warm pixels can be reduced a bit by cooling.

On the other hand, there is another effect of cooling, which can be shown for CCD and CMOS image sensors: it changes the quantum efficiency of the image sensors at different spectral wavelengths. Figure 2 shows the data from a CIS2521 image sensor, where the signal at +5°C temperature of the image sensor is used for normalization. Using LEDs at different peak wavelengths and same exposure time, images were recorded at different temperatures of the image sensor. The result is similar to measurements with a CCD. At higher wavelengths in the NIR range of the spectrum, the sensitivity decreases with the deeper temperatures, while the blue-green range is not influenced that much. Therefore for signals above 600 nm cooling might not be such a good idea: at 740 nm and at -20°C the sensitivity is decreased by 8%, and at 950 nm and +5°C by an even greater amount, 18%. This should be considered when the image sensor temperature is selected for applications with longer wavelength-emitting fluorophores.

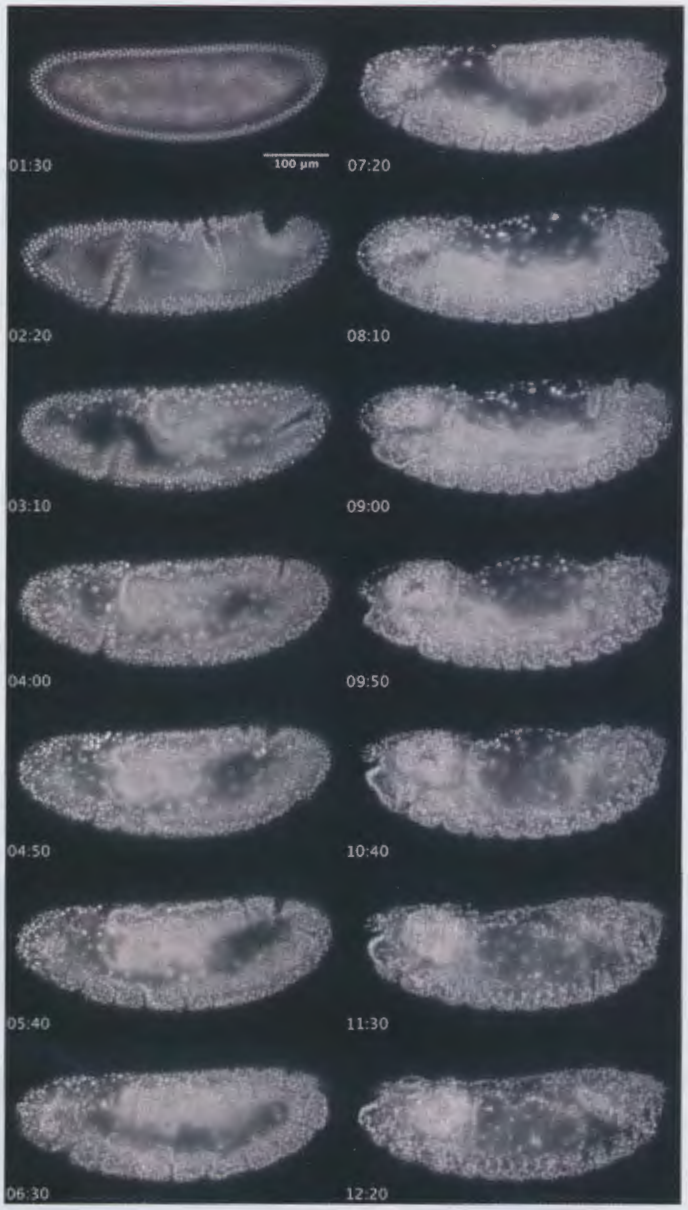

FIGURE 4
Stages of *Drosophila melanogaster* embryo development, recorded with a Zeiss LZ1 light sheet fluorescence microscope and a sCMOS camera. The embryo was marked with His-YFP, excited with 1 mW 488 nm laser light.
Images were taken every 5 minutes; shown are one optical slice from one angle every 50 minutes, from 1:30 to 11:30 hours into development.
Courtesy of C. Schmied and P. Tomancak, Max Planck Institute of Molecular Cell Biology and Genetics, Dresden, Germany and Carl Zeiss Microscopy GmbH

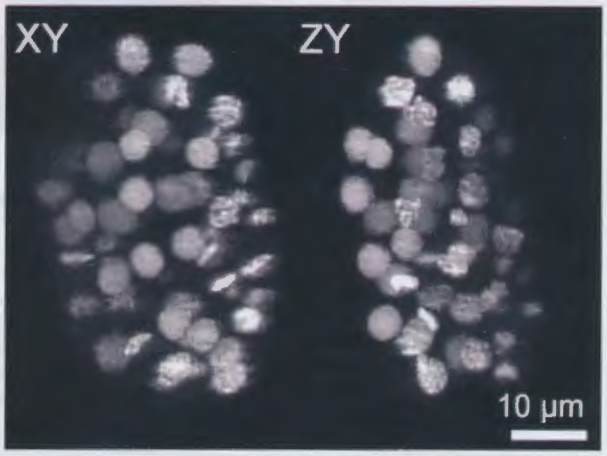

FIGURE 5
Dual view inverted selective plane illumination microscopy (diSPIM) volumetric image of histones in a live nematode embryo (*Caenorhabditis elegans* BV24). Maximum intensity XY and ZY views are shown. diSPIM allows maintaining of high spatiotemporal resolution imaging of long-term embryogenesis up to hatching
Courtesy of Y. Wu and H. Shroff, National Institute of Biomedical Imaging and Bioengineering, National Institutes of Health, Bethesda, Maryland, USA

sCMOS CAMERAS

Although introduced in 2009 to describe the first new image sensor (the CIS2521), the term sCMOS has become well known in the life sciences area of microscopy. Since then, Fairchild has introduced further versions with similar excellent features: the CIS2020, CIS1907 and CIS1210. And the offerings from camera manufacturers has grown as well such that customers now have a larger selection to choose from. From the Table we can see that currently available cameras can be grouped into three: 1. moderately cooled sCMOS cameras; 2. deeper cooled sCMOS cameras; and 3. so-called

EU

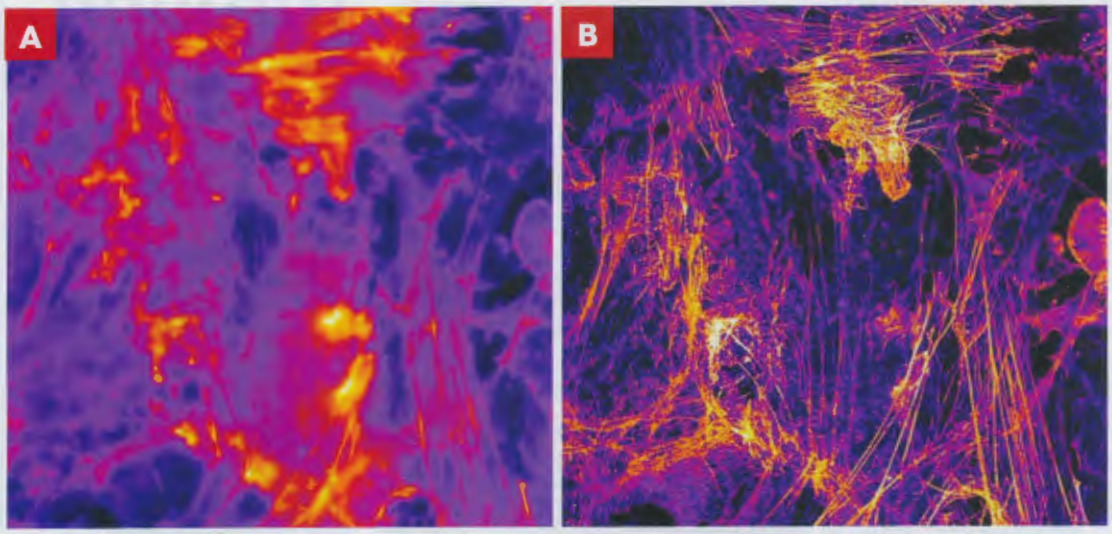

FIGURE 6
Chicken ganglion cells. F-actin has been marked with Atto488 coupled to phalloidin. (a) Maximum projection of a z-stack of 35 images. (b) Maximum projection of a z-stack of 35 images of the same sample but recorded with structured illumination using a hexagonal grid and a rolling shutter synchronous laser line illumination. The visible area is 85.3 µm x 85.3 µm

False colour coded images courtesy of Prof. Uhl, BIZ, Ludwig-Maximilian-University Munich, Germany

sCMOS cameras. The latter cameras are described here as "so-called" because they use sCMOS as a description without having CMOS image sensors with to the optimal combination of qualities of the sensor(s) from which the term originated.

MODERATEDLY COOLED sCMOS CAMERAS

The moderately cooled sCMOS cameras, as the largest group, definitively govern high frame rate applications such as localization microscopy, lightsheet microscopy, structured illumination microscopy, dual-spinning disk confocal microscopy and digital pathology, to name but a few, because all of these methods benefit from the high frame rates, low noise and high sensitivity.

For example, in localization microscopy compared to the prior EMCCD cameras the image uptake of a single result image (see Figure 3) has been improved by a time factor of 12.5, resulting now in a couple of seconds instead of minutes. In lightsheet or selective plane imaging microscopy (see Figure 4) it is now no problem to follow the morphogenesis of growing embryos like zebra fish or *Drosophila* embryos. A demand for even higher frame rates was expressed in many scientific meetings in 2013 presenting results with this method [4].

DEEP-COOLED sCMOS CAMERAS

While the deep-cooled sCMOS cameras have been used as well in these areas, they do not present any significant advantage in the higher frame rate applications. They show their benefits in the very low signal applications where frame rate is not important. For example low fluorescent indicators in fluorescence in-situ hybridization (FISH) or chemoluminescence where they compete with the established EMCCD cameras. In applications where the signal amounts to no more than a couple of photons the features of EMCCD cameras still have some advantages and often these cameras are already used there.

SO-CALLED sCMOS CAMERAS

The so-called sCMOS cameras are a collection of good-performance cameras with modern CMOS image sensors, which are really good compared with the CMOS image sensors available a couple of years ago, but due to their limited dynamic and higher readout noise do not exhibit the same combination of nice features, but could be a good alternative for standard microscopy, where a huge range of standard cameras is available. An advantage compared to the usually applied CCD cameras can be their higher frame rate.

APPLICATIONS

As described in various review publications [5, 6, 7], the new microscopy methods in their many different flavours try to push the diffraction barrier and resolve structures and processes better at cellular and even molecular levels. Many of the new methods rely on the recording of a few to many images, which are subsequently processed to create a final result image. Therefore, beside the standard requirements such as low noise and high sensitivity, a high frame rate is of importance to reduce the overall recording and process time for the image. Here I give some examples of the successful application of sCMOS cameras in the area of advanced microscopy techniques.

In addition to the example of localization microscopy shown in Figure 3, sCMOS cameras are applied in selective plane illumination microscopy (SPIM) applications, where different optical set-ups are applied nowadays, many of them using two light sheets and two cameras to create faster a stack of slices, or simultaneously record two colours, and create less stress for the sample organism. Typical results are shown in Figures 4 and 5. Figure 4 recapitulates embryogenesis of *Drosophila melanogaster*. All images show unprocessed data of one single optical section every 50 minutes, from 1:30 to 12:50 hours of development. The embryo was marked with a His-YFP staining. By this method a variety of impacts on embyrogenesis can be investigated.

In Figure 5 the result of dual view inverted SPIM (diSPIM) images are shown as two maximum projections in the x-y and the z-y plane. They show volumetric images of histones in a live nematode embryo [8]. Here two sCMOS camera were used simultaneously for the recordings, which enabled the researchers to generate sharper images with less photobleaching compared to standard methods like spinning disk confocal microscopy and SPIM with one camera. For this purpose they operated the cameras at 200 frames per second and precisely synchronized the recording with the laser light using the global reset/rolling readout feature of the CIS2521 image sensor.

In structured illumination microscopy (SIM) where a set of up to 16 images of the same focus depth are recorded with different patterns in the illumination light are recorded to calculate a final image of the focal plane, the high frame rate of the sCMOS cameras is used to reduce the recording time of a total image stack.

In the example in Figure 6 the sCMOS camera was operated at 95 MHz pixel clock and synchronized to a scanning laser line, which illuminated an exposure slit of 770 µs width. It took 28 slits and therefore approx. 30 ms total exposure per plane. For one result image in a plane 7 images have been recorded and 35 planes with a z-distance step of 100 nm have been recorded for the maximum projection shown. For comparison the maximum projection of a z-stack of confocal images is shown (Figure 6a). The resolution and contrast improvement is obvious.

Even in standard methods such as spinning disk confocal microscopy,

EU

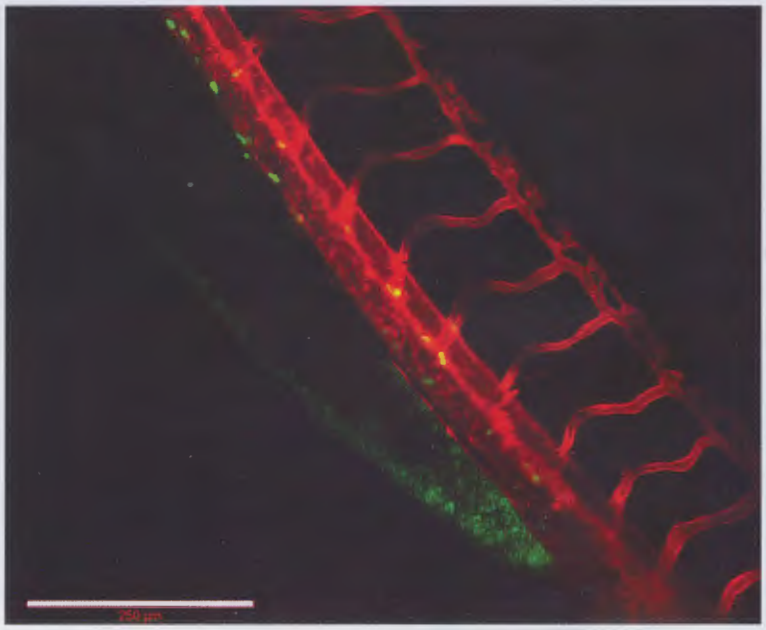

FIGURE 7
Zebrafish embryo marked with GFP (488 nm laser)and RFP (561 nm laser). Collected with VisiScope confocal microscope based on Yokogawa CSU-W1 with 25 µm pinhole and 20x objective. Single plane display from a z series. Scale bar = 250 µm.
False colour coded, Courtesy of Visitron Systems GmbH, Puchheim, Germany

sCMOS cameras can speed up the image recording due to their precise synchronization capabilities. Figure 7 shows a single plane of a GFP/RFP stained zebrafish embryo recorded with a dual spinning disk confocal scanning microscope.

WHERE DO WE GO FROM HERE?

It can be expected that more sCMOS cameras will be released to the market reflecting their popularity in life sciences applications. Maybe also specifically adapted versions will follow. On the sensor side, for example, the noise behaviour of sCMOS image sensors, especially the amount of pixels i.e. the "noise tail" (see Figure 1b) of the noise histogram, can be improved. This and a further reduction of the readout noise seem to be on the roadmap of the sensor manufacturers. As well as a higher sensitivity respectively a higher quantum efficiency in combination with further increases in image rate would be welcome, but this certainly means approaching the ideal sensor. However, the existing sCMOS cameras will be applied to push and advance microscopy techniques even further.

BREEDING GROUNDS

sCMOS image sensor technology has a great impact on microscopy. With the excellent combination of low readout noise (< 1 electron), a high dynamic range of 1:20000 to 1:33000, a high sensitivity (up to 70 % quantum efficiency) and a high resolution (up to 2560 x 2160 pixels at a very useful pixel pitch of 6.5 µm x 6.5 µm) it has been like a culture medium or breeding ground for relevant light microscopy methods. Now the question "How to measure" has been turned into "Where to store the data," which seems to be a major task for all the new methods, which go for higher throughputs in their measurements.

REFERENCES

1 Fairchild Imaging, Milpitas, CA, USA, www.fairchildimaging.com; Andor Technology, Belfast, UK, www.andor.com; PCO AG, Kelheim, Germany, www.pco.de
2 F. Huang, T. M. P. Hartwich, F. E. Rivera-Molina, Y. Lin, W. C. Duim, J. J. Long, P. D. Uchil, J. R. Myers, M. A. Baird, W. Mothes, M. W. Davidson, D. Toomre & J. Bewersdorf. *Video-rate nanoscopy using sCMOS camera-specific single-molecule localization algorithms. Nature Methods* 10:653-658, 2013.
3 J. Fölling *et al. Fluorescence nanoscopy by ground-state depletion and single-molecule return. Nature Methods* 5(11):943-945, 2008.
4 For example: *FOM 2013* (Maastricht), *MAF 2013* (Genoa), *ELMI 2013* (Arcachon), *EMBL - Seeing is Believing* (Heidelberg)
5 Stefan W. Hell. *Far-field nanoscopy. Science* 316:1153-1158, 2007;
6 J. Huisken and D. Y. R. Stainier. *Selective plane illumination microscopy techniques in development biology. Development* 136:1963-1975, 2009;
7 L. Schermelleh, R. Heintzmann and H. Leonhardt. *A guide to super-resolution fluorescence microscopy. J. Cell Biology* 190(2):165-175, 2010.
8 Y. Wu, P. Wawrzusin, J. Senseney, R. S. Fischer, R. Christensen, A. Santella, A. G. York, P. W. Winter, C. M. Waterman, Z. Bao, D. A. Colón-Ramos, M. McAuliffe, H. Shroff. *Spatially isotropic four-dimensional imaging with dual-view plane illumination microscopy. Nature Biotechnology* 31(11):1032-1038, 2013.

BIOGRAPHY

Gerhard Holst has a diploma (1991) from Technical University RWTH Aachen, and PhD (1994) in electrical engineering from the University of Dortmund. From 1991-1994 he worked at the Max-Planck-Institute for Systemphysiology, in Dortmund, and from 1994-2001 at the Microsensor Research Group, Max-Planck-Institute for Marine Microbiology in Bremen. He joined PCO AG in 2001 where he is now Head of Research Department.

ABSTRACT

In 2009 a new type of complimentary metal-oxide semiconductor (CMOS) image sensor was developed with a combination of high sensitivity, low readout noise, high frame rate, high resolution and high dynamic range. In this review, I give an overview on the matured sCMOS technology, discuss some of the wanted and unwanted features of these sensors, and describe with some applications how sCMOS technology has helped to either fuel or improve microscopy methods such as confocal microscopy, localization microscopy, selective plane imaging microscopy and structured illumination microscopy.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support and data contributions of: Yicong Wu, Hari Shroff (National Institute of Biomedical Imaging and Bioengineering, NIH, Bethesda,MD, USA), Christopher Schmied, Pavel Tomanczak (MPI for Molecular Cell Biology and Genetics, Dresden, Germany), C. Seebacher, R. Uhl (Bio-Imaging Zentrum, LMU University, Munich, Germany), Leica Microsystems GmbH, Visitron GmbH, Carl Zeiss Microscopy GmbH

CORRESPONDING AUTHOR DETAILS

Dr Gerhard Holst
Science & Research
PCO AG
Donaupark 11
93309 Kelheim, Germany
Tel: +49 (0)9441 2005 36
Email: gerhard.holst@pco.de
www.pco.de

Microscopy and Analysis 28(1):S4-S12 (EU), January 2014

Parameter	Moderately Cooled sCMOS Cameras												Deep Cooled sCMOS Cameras				So-Called sCMOS Cameras		
model	pco.edge 5.5	pco.edge 4.2	pco.edge 5.5 usb 3.0	pco.edge 4.2 usb 3.0	Zyla 5.5	Zyla 4.2	SciMOS	OptiMOS	MityCam SCMOS Vision Dev Kit	MityCam SCMOS Vision Dev Kit	?	?	pco.edge gold 5.5	pco.edge gold 4.2	Neo	Orca Flash 4.0 v2	Orca Flash 2.8	Rolera Bolt	Osprey OS4MPc-CL
manufacturer	PCO AG	PCO AG	PCO AG	PCO AG	Andor Technology	Andor Technology	Fairchild Imaging	Q-Imaging	Critical Link	Critical Link	Photonic Science	Photonic Science	PCO AG	PCO AG	Andor Technology	Hamamatsu	Hamamatsu	Q-Imaging	Raptor Photonics
image sensor	BAE CIS2521	BAE CIS2020	BAE CIS2521	BAE CIS2020	BAE CIS2521	BAE CIS2020	BAE CIS2521	BAE CIS1910	BAE CIS1910	BAE CIS1210	BAE CIS2020	BAE CIS1910	BAE CIS2521	BAE CIS2020	BAE CIS2521	BAE CIS2020	?	Sony IMX035	CMOSIS CMV4000
resolution [pixels]	2560 x2160	2048x 2048	2560x 2160	2048x 2048	2560x 2160	2048x 2048	2560x 2160	1920x 1080	1920x 1080	1280x 1024	2048x 2048	1920x 1080	2560x 2160	2048x 2048	2560x 2160	2048x 2048	1920x 1440	1280x 1024	2048x 2048
pixel size [µm²]	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	6.5x6.5	3.6x3.6	3.6x3.6	5.5x5.5
size / diagonal [mm]	16.6x14.0/ 21.8	13.3x13.3/ 18.8	16.6x14.0/ 21.8	13.3x13.3/ 18.8	16.6x14.0/ 21.8	13.3x13.3/ 18.8	16.6x14.0/ 21.8	12.4x7.0/ 14.3	12.4x7.0/ 14.3	8.3x6.7/ 10.7	13.3x13.3/ 18.8	12.4x7.0/ 14.3	16.6x14.0/ 21.8	13.3x13.3/ 18.8	16.6x14.0/ 21.8	13.3x13.3/ 18.8	6.97x5.2/ 8.7	4.6x3.7/ 5.95	11.3x11.3/ 15.9
QE [%]	>60 (590nm)	>70	>60 (590nm)	>70	60	72	>55 (550nm)	55 (600nm)	55	55	60 (550nm)	60 (550nm)	>60 (590nm)	> 70	60	> 70 (600nm)	68 (490nm)	>60 (490nm)	>63 (500nm)
readout noise [e-] median	1.1	0.9	1.1	0.9	1.2	0.9	1.2	1.5	-	-	?	1.2	?	1.1	0.9	1	0.9	-	-
readout noise [e-] rms	1.5	1.4	1.5	1.4	-	-	-	1.9	tbd	tbd	?	-	?	1.5	1.4	-	1.5	3	3
exposure time range	10µs - 2s	500µs - 10s	10µs - 2s	500µs - 10s	?	?	?	0ms - 30s	-	-	?	-	?	10µs - 2s	500µs - 10s	?	1ms - 10s	20µs - 10s	30µs - 1.9s	27.7µs - 30min
Max. full frame rate [fps]	100	100	32	40	100	100	74 (16bit) / 100 (8bit)	100	25	25	?	18 (16bit) / 37 (12bit)	?	32	40	100	30 (USB 3.0) / 100 (Camera Link)	45.4	30	37.5
fullwell capacity [e-]	30000	30000	30000	30000	30000	30000	30000	30000	-	-	?	-	?	30000	30000	30000	30000	18000	17000	12000
intra scene dynamic	1:27000	1:33000	1:27000	1:33000	1:25000	1:33000	1:25000	1:20000	-	-	?	>1:20000	?	1:27000	1:33000	1:30000	1:33000	1:4500	1:5667	1:1714
A/D conv. [bit]	16	16	16	16	12/16	12/16	8/16	16	2x11	2x11	?	12/16	?	16	16	12/16	16	12	12	12
dark current [e-/s/ pixel]	0.3	< 0.3	0.3	< 0.3	0.14	0.14	25	0.5 (0°C)	-	-	?	< 0.5	?	0.06 (-30°C)	0.06 (-30°C)	0.015 (-30°C) 0.007 (-40°C)	0.5 (-10°C) / 0.05 (-30°C)	?	NA - pixel freeze technology	< 9 (+5°C)
rolling shutter	yes	yes	yes	yes	yes	yes	yes	?	yes	yes	?	yes	?	yes	yes	yes	yes	yes	yes	yes
global shutter	yes	no	yes	no	yes	no	yes	?	-	-	?	yes	?	yes	no	yes	no	no	no	no
image sensor temp. (air cool) [°C]	5	5	-1	-1	0	0	25	0	5 - 10°C delta	5 - 10°C delta	?	40°C delta	?	-15	-15	-30	-10	5	-	5
image sensor temp. (water cool) [°C]	5	5	-1	-1	-10	-10	-	-	-	-	?	possible	?	-30	-30	-40	-30	-	-	-
interface	Camera Link full 10 tap	Camera Link full 10 tap	UBS 3.0	USB 3.0	Camera Link 3-tap / Camera Link 10-tap	Camera Link 3-tap / Camera Link 10-tap	Camera Link	SerialLite PCIe	USB 2.0 / Ethernet	USB 2.0 / Ethernet	?	GigE / Camera Link single & full	?	UBS 3.0	UBS 3.0	Camera Link or USB 2.0	Camera Link / USB 3.0	Camera Link	USB 2.0	12bit Camera Link base, 2-tap
size [mm³]	88x 76x70	88x 76x70	88x 76x70	88x76x70	133x82x80	133x82x80	151x 88x88	98x 125x178	148x 90x90	148x 90x90	?	?	?	132x83x76	132x 83x76	160x 144x120	125x 86x85	150x95x95	95x85x71	95.9x65x 61.5
weight [g]	700	700	930	930	1000	1000	1225	1720	-	-	?	?	?	1800	1800	3400	2000	1500	540	<432

Overview of available sCMSO cameras. If the manufacturer does not provide the specific information, a question mark '?' is used; if the parameter is not applicable a dash '–' is used.